RAPID SEISMIC RISK EVALUATION SYSTEM OF EXISTING BRIDGES IN TAIWAN

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ABSTRACT :

Located at the western Circum Pacific Seismic Belt, Taiwan suffers from earthquakes frequently caused by the interactive extruding at the interface between the Philippine Ocean Plate and the Euro-Pacific Plate. Numerous existing bridges in Taiwan are inevitably threatened by the occurrence of strong earthquakes. Therefore, the establishment of a rapid seismic risk evaluation system could help in reducing seismic disaster of the bridges. Based on the recorded earthquakes with magnitude over 5.0 during 1990 to 2003, this paper performed the regression analyses of attenuation law of peak ground acceleration (PGA) for the stations, all over Taiwan, set up by the CWB under the Taiwan Strong Motion Instrumentation Program. The comparisons between simulated seismic intensity and actual one for some recent earthquakes were made sequentially to assure the precision of analysis. As a result, the distribution of PGA, for any simulated earthquake, over Taiwan can be predicted successfully and served as the basis of seismic demand evaluation. On the other hand, according to the investigations of seismic capacity for over 2,000 existing bridges performed by the Taiwan Directorate General of Highways, the fragility curves of the bridges can be implemented and employed in calculating the probabilities for various damage levels. Accordingly, this paper adopted the object-oriented technique to develop the evaluation system. The possible seismic loss of the bridges under a specific simulating earthquake could be evaluated in a short moment and shown visually. The developed system might facilitate the careful strategy of disaster-preventing.

KEYWORDS: Attenuation law; Fragility curve; Disaster-preventing strategy; Object-oriented

1. INTRODUCTION

In Taiwan, threat of earthquake to the numerous existing bridges is inevitable and how to mitigate the resulting disasters becomes an important issue in seismic engineering. The bridge with slight or moderate seismic damage could decrease its serviceability and transportability of vehicles. Moreover, the severe damage or even the collapse of which would peril the structural safety and break the trafficability to lose the functionality of life-line system. Therefore, the seismic risk evaluation system is needed urgently for estimation of seismic loss of the existing bridges. By that, the seismic capacity of the bridges could be identified quickly and the priority of repairing or retrofitting for the unqualified bridges could be made to optimize the rehabilitation efforts within limit budget. Accordingly, the network of highway for disaster-preventing is able to be planned thoroughly.

A good seismic risk evaluation system of the existing bridges at least consists of four fundamental elements: (1) precise simulation of earthquake, (2) abundant data-base of seismic capacity of the bridges, (3) capability of rapid evaluation of seismic loss and (4) visualized operation system. The first one deals with nonlinear regressive analysis of attenuation law of peak acceleration (PGA). A relationship between PGA, seismic magnitude M and focus distance R is established to do the earthquake simulation. The second one relates to performing seismic evaluation of the numerous existing bridges through pushover analysis or time history analysis. From which, various structural damage statuses are able to be defined and relevant statistic analysis can be done to obtain the fragility curves for seismic loss estimation. The third one concerns rapid calculation of probabilities with respect to various damage statuses under the situation of a specific earthquake. The cost as well as time required for seismic repairing or retrofitting of the bridge could be estimated instantly. The last one associates computer technology of software with hardware to exhibit visualization of operation system. The objective-based technique is implemented to enhance the flexibility of system expanding.

This paper intends to complete a system with the advantages above. The possible seismic loss of the bridges under a specific simulating earthquake could be evaluated in a short moment and shown visually. The developed system might facilitate the careful strategy of disaster-preventing.

2. CALIBRATION AND INVESTIGATION OF ATTENUATION LAW OF PGA

The attenuation law of PGA in Campbell's form was adopted and expressed as

$$PGA(gal) = a\exp(bM)[R + c\exp[dM]]^{-e} \tag{2.1}$$

Where M is the seismic magnitude; R focus distance; constants of a~e are the parameters to be determined. Nonlinear regression method used here is shown as follow:

$$Y_i = f\left(X_i, \gamma_p\right) + \varepsilon_i \tag{2.2}$$

where Y_i and $f(X_i, \gamma_p)$ are the measured and the prediction, respectively, of the i-th dependent variable; X_i is the i-th variable; γ_p is the p-th parameter in regressive expression; ε_i is the residual deviation between Y_i and $f(X_i, \gamma_p)$, which can be expressed as

$$e = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix} = \begin{bmatrix} Y_1 - f\left(X_1, \gamma_p\right) \\ Y_2 - f\left(X_2, \gamma_p\right) \\ \vdots \\ Y_n - f\left(X_n, \gamma_p\right) \end{bmatrix} = \mathbf{Y} - f\left(\mathbf{X}, \boldsymbol{\gamma}\right) \tag{2.3}$$

As a result, the sum of the squares of the residual deviation can be written as:

$$S_e = \sum_{i=1}^{n} \varepsilon_i^2 = e^T e \tag{2.4}$$

In Eq. (2.3), let the detected data of PGAs be Y and $f(X, \gamma)$ be the right hand side of Eq. 2.1 ; n be the number of the detected PGAs; γ_p be the coefficients of *a~e*. Finally, p identical to 5 is the number of γ_p in the regression equation, Eq. (2.1). By solving following optimal problem, the optimal values of *a~e* can be obtained.

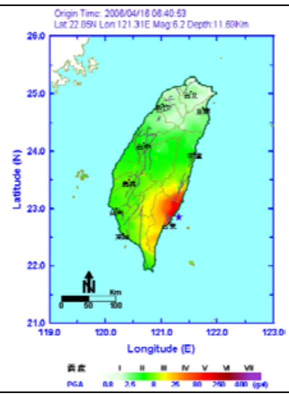
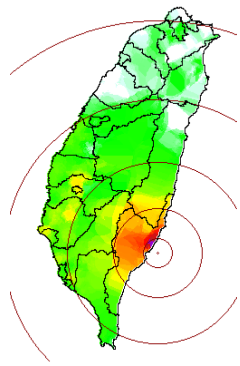
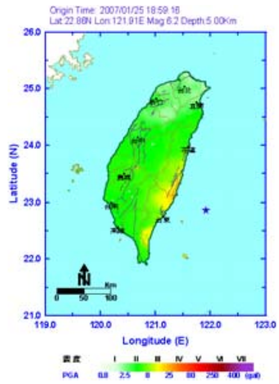
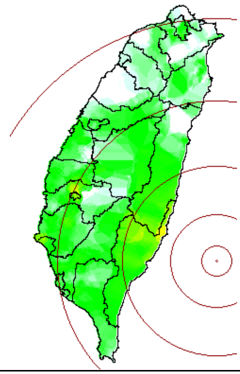
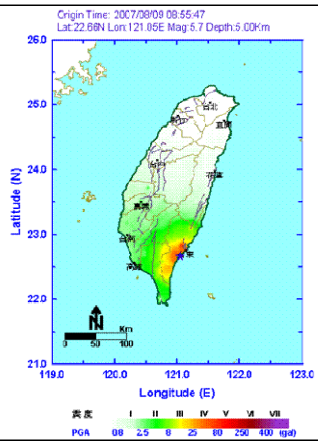
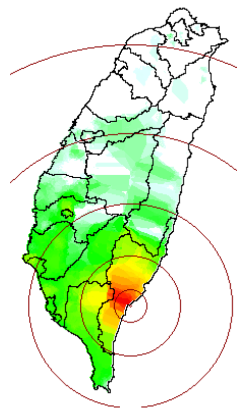
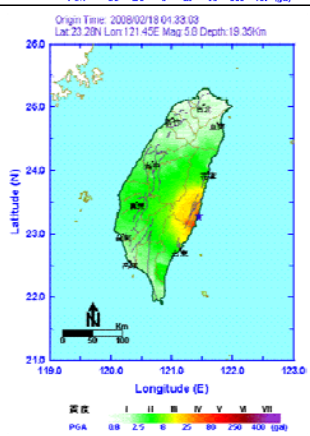
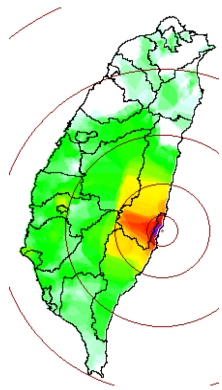
$$\min S_e = \min\left(\sum_{i=1}^{n} \varepsilon_i^2\right) = \min\left(e^T e\right) \tag{2.5}$$

Without taking the derivation of objection function as Eq. 2.5, the Nelder-MEAD simplex method (Lagarias *et al.* 1998) is quite efficient and was employed as the optimization solver.

Based on the recorded earthquakes with magnitude over 5.0 during 1990 to 2003, this paper performed the regression analyses of attenuation law of *PGA* for the stations, all over Taiwan, set up by the CWB under the Taiwan Strong Motion Instrumentation Program.

The comparisons between simulated seismic intensity and actual one announced by CWB for some recent earthquakes were made and shown in Table 1. It can be seen that the distributions of simulated seismic intensity are close to the ones announced by CWB. Therefore, the analysis could predict the simulated earthquake within an acceptable precision.

Table 1 Comparisons between simulated seismic intensity and actual ones announced by CWB

Time	**Magnitude**	**Depth**	**Result**	
			CWB	Simulated
06 / 04 / 16 06 : 40	6.2	11.69		
07 / 01 / 25 18 : 59	6.2	5.00		
07 / 08 / 09 08 : 55	5.7	5.00		
08 / 02 / 18 04 : 33	5.8	19.35		

3. IMPLEMENTATION OF SEISMIC CAPACITY OF EXISTING BRIDGES

For the past few years, the concept of performance-based seismic evaluation (PBSE) introduced by the ATC-40 has been gradually accepted by structural engineers. However, deficiencies of the proposed procedure still exist. Recently, Sung et al. suggested some modifications for the ATC-40 procedure to improve the efficiency significantly. A new approach evaluating the full range of the corresponding seismic demand with respect to each performance point during the life of structures was proposed. The necessary link between PGA and various structural performances could be obtained.

Based on that, the PBSE for over 2,000 existing bridges (Fig. 1) in Taiwan have been conducted by the Taiwan Directorate General of Highways. Accordingly, the fragility curves were developed analytically with respect to PGA for seismic damage assessment of the bridges. Since the seismic capacity of a bridge can be interpreted with a bi-linear diagram represented by PGA versus structural displacement (Sung, 2005), this study defines four performance objectives: (1) structural performance behaves below 80% of yielding (PO_1); (2) structural performance reaches yield (PO_2); (3) structural displacement experiences two-thirds of ductility capacity (PO_3) and (4) structural displacement exhausts all of ductility capacity as shown in Fig. 2. The fragility curves are constructed assuming a normal distribution. For the cumulative probability $P_i(\geqq R_i)$ of occurrence of the damage equal or higher than level PO_i is given as

$$P_i\left(\geq PO_i\right) = \Phi\left(\frac{X-\mu_{X_i}}{\sigma_{X_i}}\right) \tag{2.6}$$

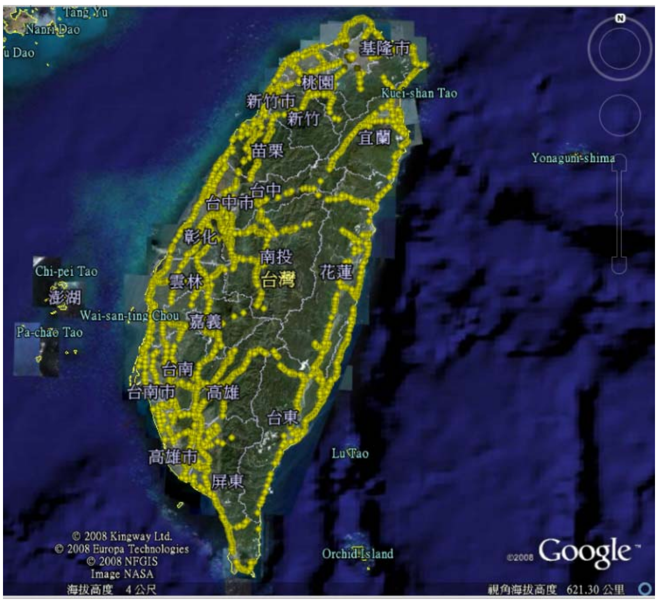


Figure 1. Locations of the existing bridges with PBSE

Where Φ is standard normal cumulative distribution function; μ_{X_i} and σ_{X_i} are the mean and standard deviation, respectively, of i-th damage level R_i represented by X. i.e. the peak ground acceleration. As a result, the probabilities $P_r(R_i)$ corresponding five damage limit statuses including (1) No damage R_i; (2) slight damage R_2; (3) moderate damage R_3; (4) extensive damage R_4 and (5) complete damage R_5, as shown in Fig. 3, can be drawn out of four $P_i(\geqq PO_i)$, $i=1\sim4$ as following equation:

$$\begin{aligned} P_r(R_1) &= P_1 \\ P_r(R_i) &= P_i - P_{i-1} \quad ,i = 2 \sim 4 \\ P_r(R_5) &= 1 - P_4 \end{aligned} \tag{2.7}$$

If the direct cost of each damages limit status is expressed as $Cost\_R_i(i=1\sim5)$, the total direct cost, for the repairing or retrofitting of the bridge subject to a specific PGA could be written as

$$TOTAL\_DIRECT\_COST = \sum_{i=1}^{5} COST\_R_i \times P_r(R_i) \tag{2.8}$$

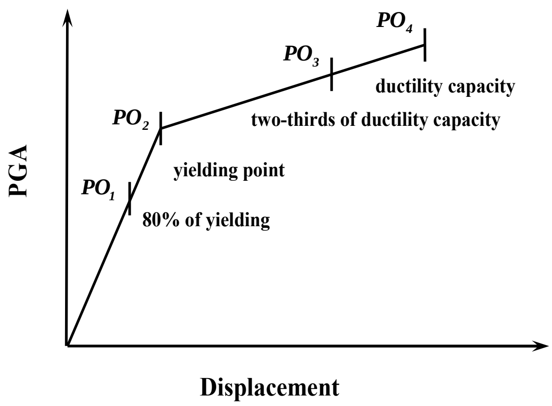


Figure 2. Four performance objectives

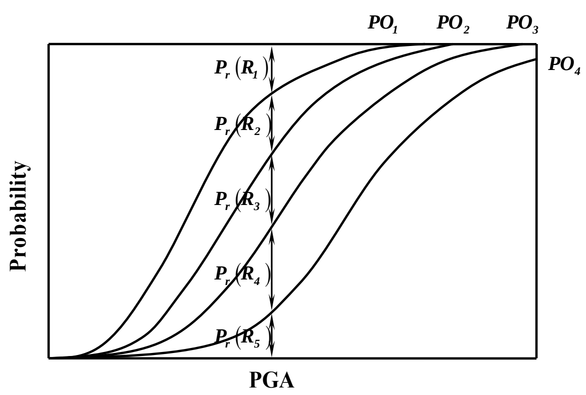


Figure 3. Fragility curves

4. DEVELOPED RAPID SEISMIC RISK EVALUATION SYSTEM

Objective-based (O.O.) technique was employed to do the planning and management of the rapid seismic risk evaluation system. Three important characteristics of O.O. including encapsulation, inheritance and polymorphism benefits greatly the reuse, easy maintenance and expansion of the developed program and are explored with C# language in the system.

Library of the regressed attenuation laws of PGA corresponding to 708 stations with ground accelerometer in

Taiwan was implemented as the data-base of seismic demand. By capturing the geographic information of seismic focus and any specific bridge site, the PGA at site can then be calculated by interpolation with those of three stations most adjacent. On the other hand, library of fragility curves with respect to various damage statuses for the bridges were implemented as the data-base of seismic capacity. These two libraries are both packaged for convenience of data-update and reuse.

The analysis can be grouped in a project so that all the inputs and the outputs can be managed systematically. Some packages of seismic loss evaluation in the developed system were shown in Fig. 4.

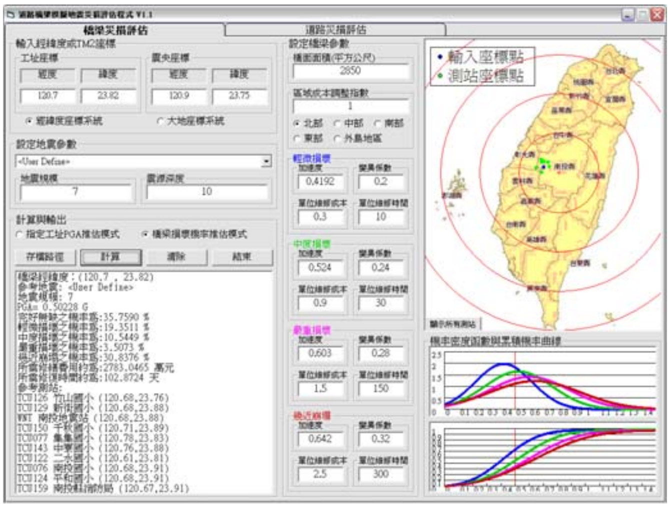


Figure 4. Rapid seismic loss evaluation system

5. CASE STUDY ON SEISMIC RISK ANALYSIS OF THE EXISTING BRIDGES

A prototype bridge located at 120.3099 E longitude and 23.5482 N latitude, shown in Fig. 5, is constructed according to the 1983 AASHTO specification of the Highway bridge. This bridge is a simply-supported post-tensioned reinforced concrete I-girder structure with the length of approximately 40m, the width of 12^{m}, and a weight of 8946.7^{kN}. The piers are designed with assumed height of substructure, diameter, nominal design strengths of concrete, longitudinal reinforcement and transverse reinforcement to be 10^{m}, 2.5^{m}, 20.6^{MPa}, 412.02^{MPa}, and 274.68^{MPa}, respectively. The longitudinal reinforcement (area ratio) for the bridge piers is taken as 1.23%, while the tie reinforcement (volumetric ratio) is taken as 0.025%. Bearing supports are hinge and roller respectively on either top of the column. Based on the seismic evaluation, the fragility curves corresponding to various damage statuses can be obtained as Fig. 6.

If a simulated earthquake with seismic magnitude M=7.2, focus depth D = 14^{km} and epicenter at 120.3019 E longitude and 23.1773 N latitude is taken into accounted, the estimated PGA at site of the bridge is PGA=0.18g. The resulting probabilities of various damage statuses are calculated as $P_r(R_1)$=65.6496 %, $P_r(R_2)$=5.9350%, $P_r(R_3)$=6.3965%, $P_r(R_4)$=3.4745 % and $P_r(R_5)$=18.5444%, respectively. Therefore, the total direct cost for the repairing or retrofitting of the bridge can be obtained TOTAL_DIRECT_COST = NT$2,608,000

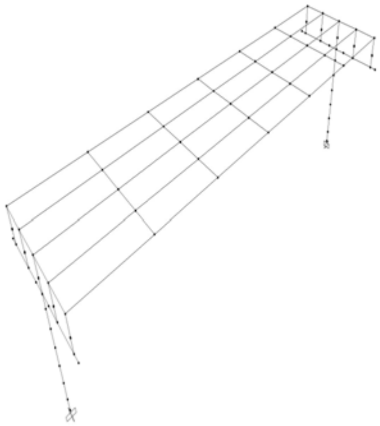


Figure 5. Structural model of bridge

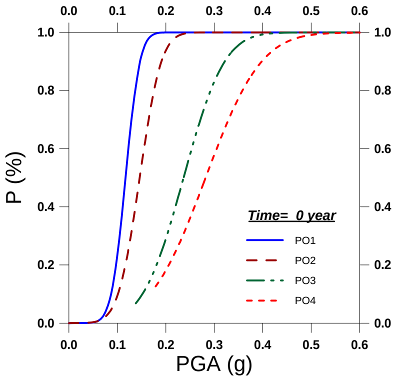


Figure 6. Fragility curves w.r.t. various damage statuses

6. CONCLUSIONS

1. The comparisons between simulated seismic intensity and actual one for some recent earthquakes were made to assure the precision of the regression analyses of attenuation law of PGA which can be served as the basis of seismic demand evaluation.
2. According to the investigations of seismic capacity for over 2,000 existing bridges performed by the Taiwan Directorate General of Highways, the fragility curves of the bridges can be implemented and employed in calculating the probabilities for various damage levels.
3. The developed object-oriented-based seismic loss evaluation system of the bridges could estimate the possible seismic loss of the bridges under a specific simulating earthquake in a short moment and shown visually. The developed system might facilitate the careful strategy of disaster-preventing.

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